



TECHNICAL NOTE

D-1307

ESTIMATION OF CRITICAL TEMPERATURE FOR SURFACE ION
CURRENTS FROM ELECTRON EMISSION DATA

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SUMMARY

E-1544

A method of calculating a relation for the critical surface temperature for ion current emission is presented. The method is based on the S-shaped electron emission curves for surfaces in the presence of ionizable vapors and upon the assumptions of thermodynamic equilibrium involved in the Saha-Langmuir relation. A comparison of the critical temperatures so calculated with the relation obtained from actual ion emission data on the cesium-tungsten system shows good agreement over a wide current density range.

Critical temperatures for cesium ion current densities of 0.21 and 1.9 amperes per square centimeter calculated by this method are presented for surfaces of rhenium, molybdenum, tantalum, and niobium. Tentative relations of the form $\log j = A_p + \frac{B_p}{T}$ are presented for these same systems, where j is the ion current density, A_p and B_p are constants, and T is the temperature.

INTRODUCTION

The use of surface ionization as a means of producing ions for ion rockets has become of considerable importance in the last few years. For engines using the surface ionization technique, by far the greatest power loss, and hence the factor governing the power efficiency, is the radiated power loss from the emitter surface. This power loss is, of course, a strong function of the surface temperature.

The temperature to which an emitter surface must be heated to assure that nearly all atoms that fall upon it will be emitted as ions has been called the critical surface temperature. For the systems that have been investigated it has been established that this critical temperature is dependent upon the total particle current density, or the rate at which

particles fall upon the surface. In fact, for the systems (combinations of surface and propellant) for which such data have been obtained, the ion current density - critical surface temperature relation can be expressed by a relation of the form:

$$\log j = A_p + \frac{B_p}{T} \quad (1)$$

where A_p and B_p are constants.

Such relations, however, exist (to the author's knowledge) only for the combinations, cesium, rubidium, or potassium on tungsten (ref. 1). Moreover, the current density range for which these data were obtained is considerably below the current density range of interest for application to ion rockets.

A field of allied interest, however, namely thermionic energy conversion, also employs the heated refractory metals in the presence of ionizable vapors as electron emission sources. One type of data of particular interest in this area is the electron emission current as a function of the surface temperature and the pressure of the surrounding vapor. A typical set of such data is shown in figure 1, which is from reference 2.

Of special interest in this respect is a recent technique (ref. 3) whereby data of the sort shown in figure 1 may be obtained at considerably higher emission current densities and higher surrounding gas pressures than were previously attainable. The data of reference 3 are reproduced as figure 2 in this report.

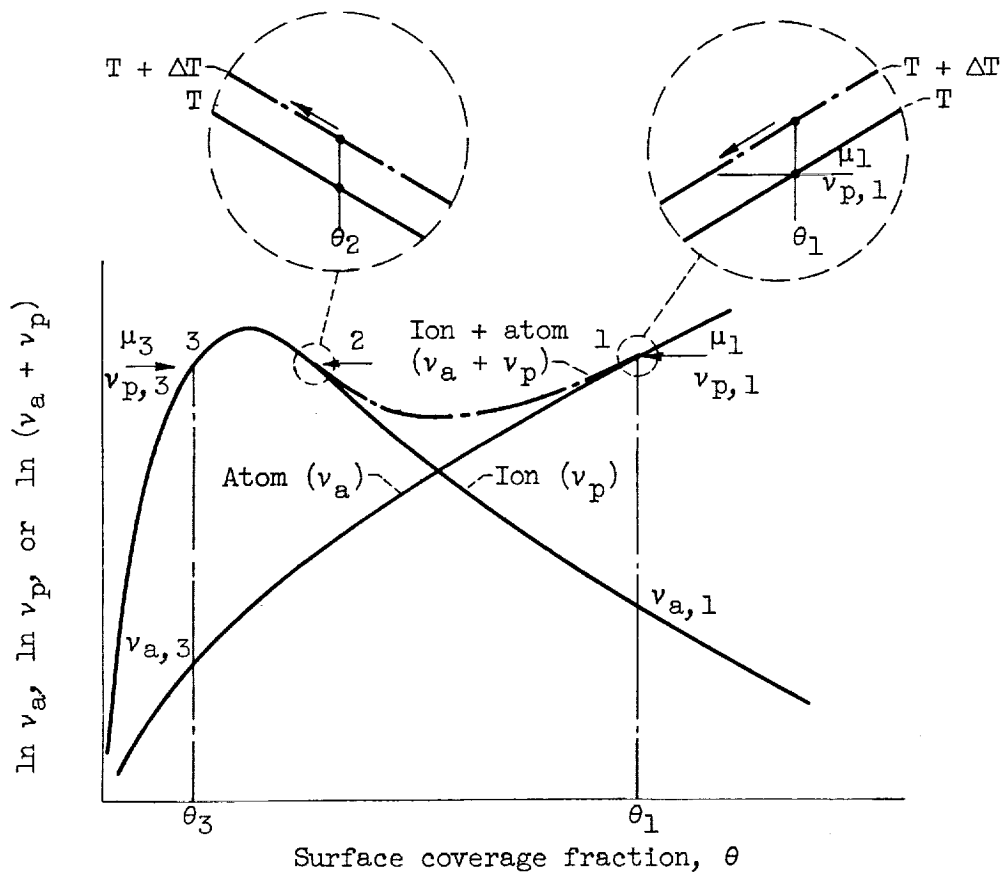
It was this latter development that prompted the look into the possibility of using these electron emission curves at high surrounding gas pressures to obtain critical temperature - ion current density relations.

This report describes a technique of calculating an ion current density - critical temperature relation from electron emission current data of the type shown in figures 1 and 2. A comparison of the relation calculated in this manner with that obtained from the actual ion and atom evaporation measurements with cesium on tungsten is shown. Finally, some tentative relations for the combinations of cesium on rhenium, molybdenum, tantalum, and niobium obtained from the data of reference 3 are presented.

ANALYSIS

The method of obtaining the ion current density - critical temperature relation from the atom and ion evaporation rate curves is described in reference 4. It will be reviewed here briefly so that the ideas of the present report may be adequately introduced.

The logarithms of the neutral atom and ion evaporation rates v_a and v_p , respectively, and the total particle evaporation rate $v_a + v_p$ are plotted as functions of the surface coverage fraction θ for a particular value of surface temperature, as shown in sketch (a). (Symbols are defined in the appendix.)



Consider a condition of operation as at point 1. The surrounding gas pressure corresponds to an arrival rate of μ_1 . The equilibrium coverage, then, corresponds to the value θ_1 , and the ion and neutral atom evaporation rates are $v_{p,1}$ and $v_{a,1}$ respectively. This is a condition of low ionization efficiency (low ion to neutral atom evaporation rates) - a stable operating condition. For instance, a small increase in the surface temperature (insert in sketch (a)) would cause a corresponding increase in the evaporation rate. Since this new evaporation rate is larger than the previous equilibrium evaporation rate (and larger than the arrival rate), the surface coverage will decrease until a new equilibrium θ is again established, at which the evaporation and arrival rates are equal.

At a point such as 2, however, the operation is not stable. Here a small increase in the surface temperature will again cause an increase in the evaporation rate. This will cause a decrease in the surface coverage, in the manner just described. However, in this region, as θ decreases, the evaporation rate increases still more. In this situation the coverage θ will continue to decrease until it reaches a value at which the evaporation rate and arrival rate are again equal. This will be on a portion of the total evaporation rate curve of positive slope (point 3 in sketch (a)) where the coverage fraction is θ_3 , ion current, $v_{p,3}$, and neutral atom current, $v_{a,3}$. This point is a condition of high ionization efficiency (high ion to atom evaporation rate).

It can now be seen that, if initially a system were in operation at a low ionization efficiency condition, such as point 1, and the surface temperature were slowly increased, the surface coverage would decrease gradually. The ion current v_p would gradually increase.

When the minimum in the total evaporation rate curve is reached (a point that corresponds closely to equal ion and neutral atom evaporation rates, that is, to an ionization efficiency of about 50 percent), the surface coverage goes suddenly over to the stable region of low θ and high ionization efficiency. The temperature at which this sudden increase in operation to a high ionization efficiency occurs is referred to as the critical temperature for surface ionization.

Since the minimums in the total evaporation rate curves occur for values of θ such that the ionization efficiency is approximately 50 percent, the Saha-Langmuir relation (ref. 5) for ionization efficiency at $T = T_{cr}$ may be written as

$$\frac{v_p}{v_p + v_a} = \left\{ 1 + \frac{g_a}{g_p} \exp \left[\frac{-q(\varphi_{eff} - V_1)}{kT_{cr}} \right] \right\}^{-1} = \frac{1}{2} \quad (2)$$

This relation is applicable to gas-metal systems in thermodynamic equilibrium. For alkali metals, $g_a/g_p = 2$. Thus, equation (2) reduces to

$$\varphi_{\text{eff}} - V_i = 6 \times 10^{-5} T_{\text{cr}} \quad (3)$$

In equation (3), φ_{eff} is the effective work function of the surface:

$$\varphi_{\text{eff}} = \varphi_e - V_c \quad (4)$$

where

φ_e work function of clean metal surface

V_c contact potential difference due to the adsorbed surface layer

Substitution of equation (4) into (3) yields

$$V_c = (\varphi_e - V_i) - 6 \times 10^{-5} T_{\text{cr}} \quad (5)$$

This is the value of contact potential difference that will yield 50-percent ionization efficiency for the Saha-Langmuir relation. For any given system φ_e and V_i are constants, so equation (5) represents one relation between the contact potential difference and the critical temperature.

The contact potential can be calculated from the electron emission data for a system. For a clean metal surface, the electron emission current density is given by

$$j_{e,o} = AT^2 \exp\left(\frac{-q\varphi_e}{kT}\right) \quad (6)$$

With an adsorbed layer on the surface, the electron emission will be greater in general because the adsorbed layer lowers the effective work function

$$j_e = AT^2 \exp\left(\frac{-q\varphi_{\text{eff}}}{kT}\right) \quad (7)$$

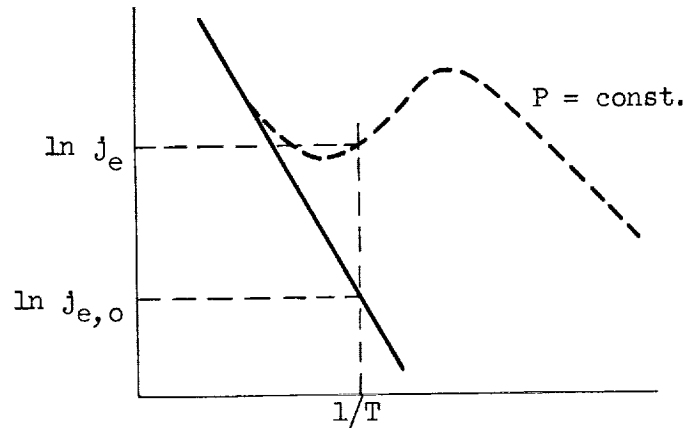
At constant temperature, dividing equation (7) by (6) and substituting equation (4) give

$$\frac{j_e}{j_{e,o}} = \exp\left(\frac{qV_c}{kT}\right) \quad (8)$$

or, solving for V_c results in

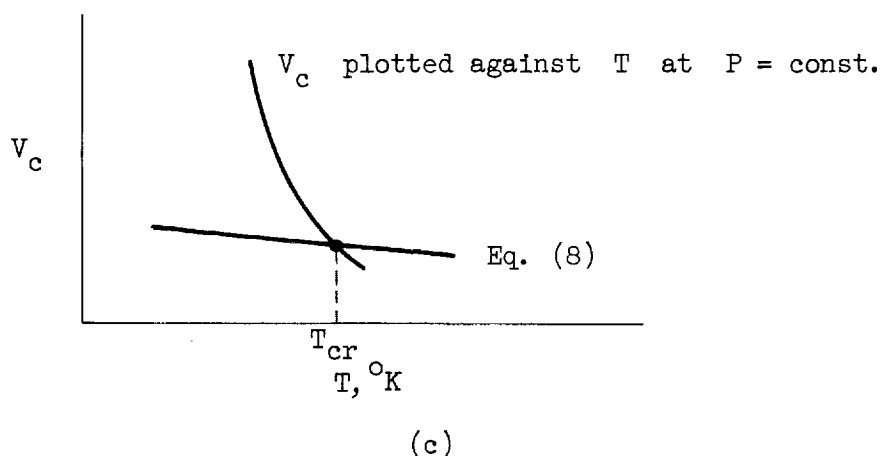
$$V_c = \frac{kT}{q} \ln\left(\frac{j_e}{j_{e,o}}\right) = \frac{T}{11,600} \ln\left(\frac{j_e}{j_{e,o}}\right) \quad (9)$$

The data curves of the type of figure 1 provide the information to calculate V_c as a function of the surface temperature and the gas pressure.



(b)

The solid line in sketch (b) is the electron emission for the clean metal surface of work function ϕ_e . The dashed line is the actual electron emission for a surrounding gas pressure P . For a particular gas pressure, the values of V_c are calculated by means of equation (9) as a function of surface temperature. This procedure yields a second relation between V_c and the surface temperature. If this relation between V_c and T is plotted along with equation (8), the intersection determines the value of $T = T_{cr}$ that satisfies both relations (see sketch (c)):



A value of T_{cr} is thus determined for a particular surrounding gas pressure.

This gas pressure and accompanying equilibrium gas temperature determine the arrival rate of gas atoms onto the surface, and thus the ion current density for operation at conditions where nearly all the atoms are ionized. The critical temperature that is thus determined, then, is the one to be associated with an ion particle current density calculated from the arrival rate at that pressure:

$$v_a + v_p = \mu_a = \frac{3.52 \times 10^{22} P}{\sqrt{TM}}, \quad (\text{cm}^{-2})(\text{sec}^{-1}) \quad (10)$$

or

$$j = 5.63 \times 10^7 \frac{P}{\sqrt{TM}}, \quad \text{amp/m}^2 \quad (11)$$

where P is the gas pressure in millimeters of mercury and M is the molecular weight.

RESULTS OF CALCULATIONS

A comparison of the results of calculating an ion current density - critical temperature relation for the cesium-tungsten system by the method just described with the relation presented in reference 4 is shown in figure 3.

The solid line of figure 3 is a plot of the equation from reference 4:

$$\log j = 11.3 - \frac{13,200}{T_{cr}} \quad (12)$$

The points shown on the figure were all calculated as explained in the ANALYSIS section. The three lowest current density points correspond to cesium arrival rates of 10^{11} , 10^{14} , and 10^{17} atoms per square centimeter per second on figure 1. The two higher density points were calculated from the data of figure 2, which correspond to cesium arrival rates of 1.3×10^{18} and 1.2×10^{19} atoms per square centimeter per second.

The points, in general, fall at slightly higher temperatures than would be obtained from equation (12) at the same current density. However, the closeness of approach of the temperature to the curve throughout the whole range is considered very good in view of the assumptions involved in their derivation, namely, that the minimums in the j against θ curves correspond to 50-percent ionization efficiency points, and that this efficiency may be determined by the Saha-Langmuir relation using contact potential values determined from electron emission data.

Corresponding values of critical temperature calculated in the same manner for cesium on rhenium, tantalum, molybdenum, and niobium from the curves of figure 2 were calculated and are shown in the following table:

Particle arrival rate, μ , (cm^{-2})(sec^{-1})	Ion current density, j , amp/ cm^2	Critical temperature, T_{cr} , $^{\circ}\text{K}$				
		Tungsten	Rhenium	Tantalum	Niobium	Molybdenum
1.3×10^{18}	0.21×10^4	1688	1760	1700	1775	1648
1.2×10^{19}	1.9×10^4	1935	1945	1940	1885	1885

An equation of the form $\log j = A + \frac{B_p}{T_{cr}}$ was generated for each system using only the two points for each system in the table:

Tungsten:

$$\log j = 10.8 - \frac{12,600}{T}, \text{ amp/m}^2 \quad (13)$$

Rhenium:

$$\log j = 13.4 - \frac{17,700}{T}, \text{ amp/m}^2 \quad (14)$$

Tantalum:

$$\log j = 10.9 - \frac{12,900}{T}, \text{ amp/m}^2 \quad (15)$$

Niobium:

$$\log j = 19.6 - \frac{29,000}{T}, \text{ amp/m}^2 \quad (16)$$

Molybdenum:

$$\log j = 10.9 - \frac{12,400}{T}, \text{ amp/m}^2 \quad (17)$$

In lieu of any actual data on the critical temperature ion current density for the systems other than tungsten, equations (14) to (17) might be used.

How these equations compare with the true relations for these systems is, of course, not known at present. The assumption has been made that the system obeys the thermodynamic predictions of the Saha-Langmuir relation. That all systems do not follow this relation has been demonstrated experimentally (ref. 5). Certainly, if the ionization efficiency for a system deviates much from the predictions of equation (2), the present technique would not be expected to apply.

CONCLUDING REMARKS

A method has been presented for calculating a critical temperature for ion current emission using the electron emission current characteristics of a surface in the presence of ionizable vapors to obtain values of contact potential. The values of contact potential were then used in the Saha-Langmuir relations to obtain the 50-percent ionization efficiency condition from which the critical temperature relation could be determined.

The method yielded a relation in very good agreement with that obtained from actual ion emission data for the cesium-tungsten system.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, March 1, 1962

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APPENDIX - SYMBOLS

A	constant in electron emission equation, $120 \text{ amps}/(\text{cm})^2(^{\circ}\text{K})^2$
A_p	constant, eq. (1)
B_p	constant, eq. (1)
g_a	statistical weight of atom
g_p	statistical weight of ion
j	ion current density, amp/m^2
j_e	electron current density, amp/cm^2
$j_{e,o}$	electron current density of clean surface, amp/cm^2
k	Boltzmann constant, $\text{ev}/^{\circ}\text{K}$
M	molecular weight
P	pressure, mm Hg
q	electron charge, coulombs
T	temperature, $^{\circ}\text{K}$
T_{cr}	critical temperature, $^{\circ}\text{K}$
V_c	contact potential, v
V_i	ionization potential, v
θ	fraction of monolayer surface coverage
μ	particle arrival rate, $(\text{cm}^{-2})(\text{sec}^{-1})$
v_a	atom evaporation rate, $(\text{cm}^{-2})(\text{sec}^{-1})$
v_e	electron emission rate, $(\text{cm}^{-2})(\text{sec}^{-1})$
v_p	ion evaporation rate, $(\text{cm}^{-2})(\text{sec}^{-1})$
ϕ_e	electron work function of clean surface, ev
ϕ_{eff}	electron work function of actual surface, ev

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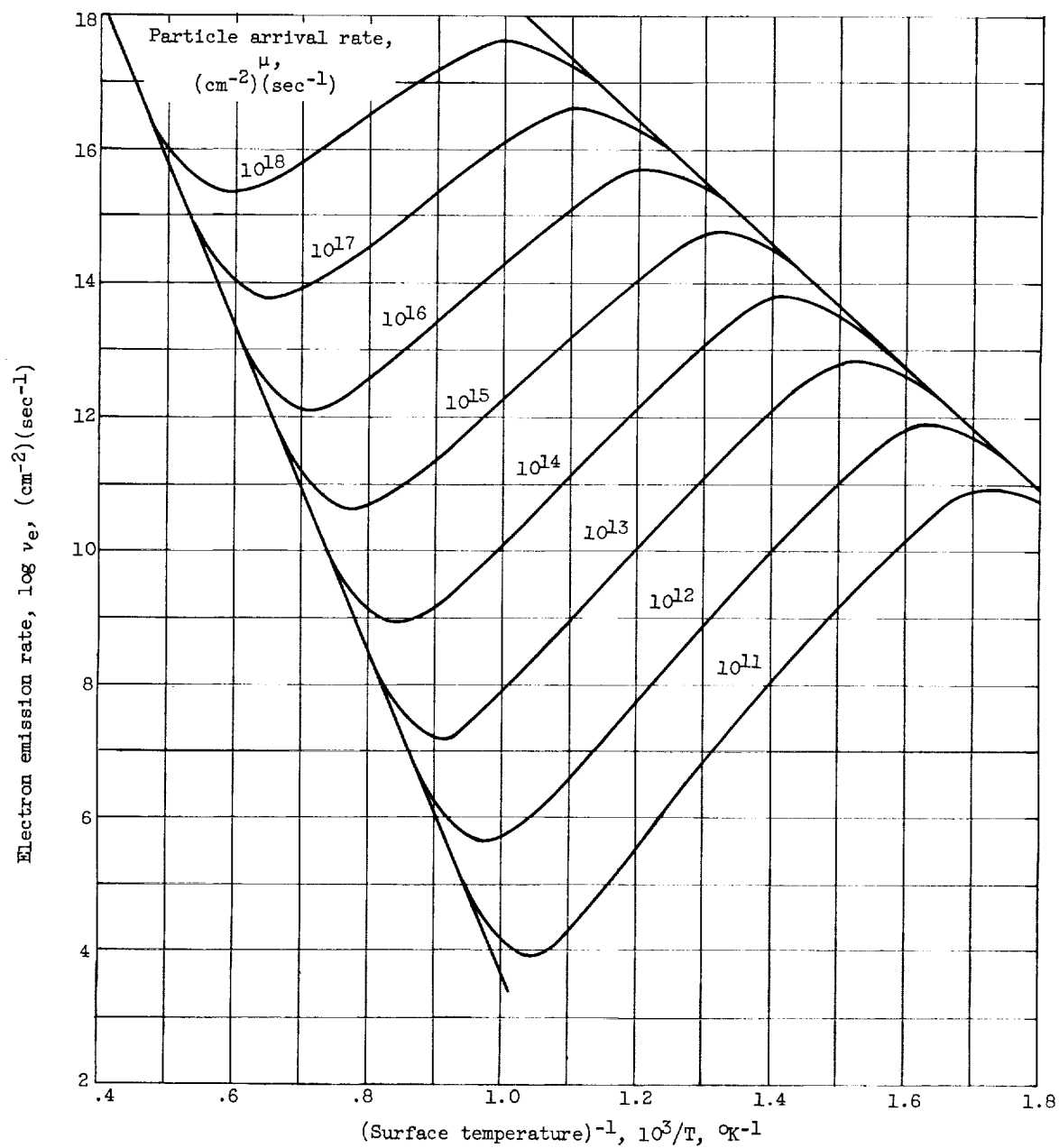


Figure 1. - Electron emission from tungsten surface in cesium atmosphere (ref. 2).

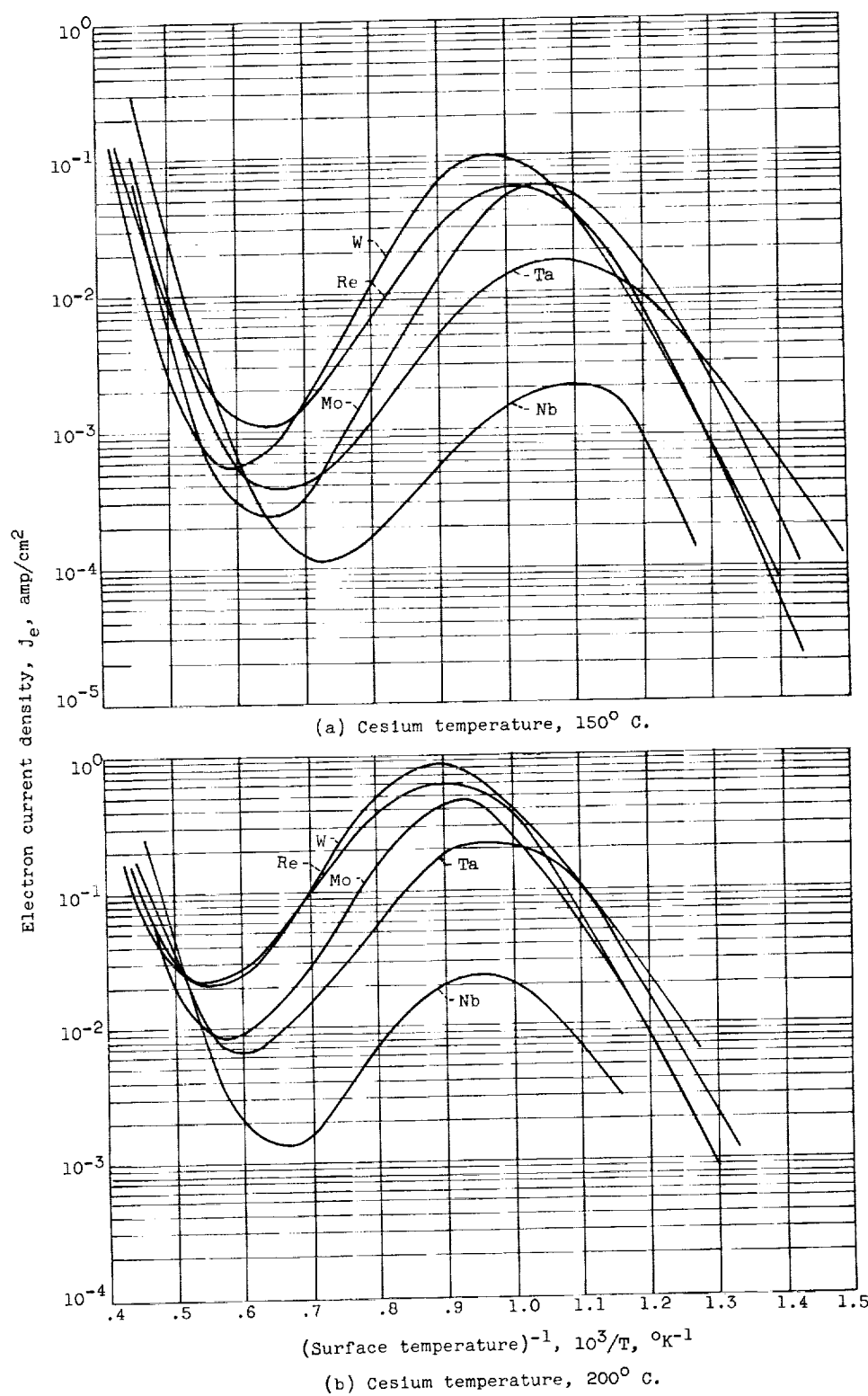


Figure 2. - Electron emission from various surfaces in cesium atmosphere (ref. 3).

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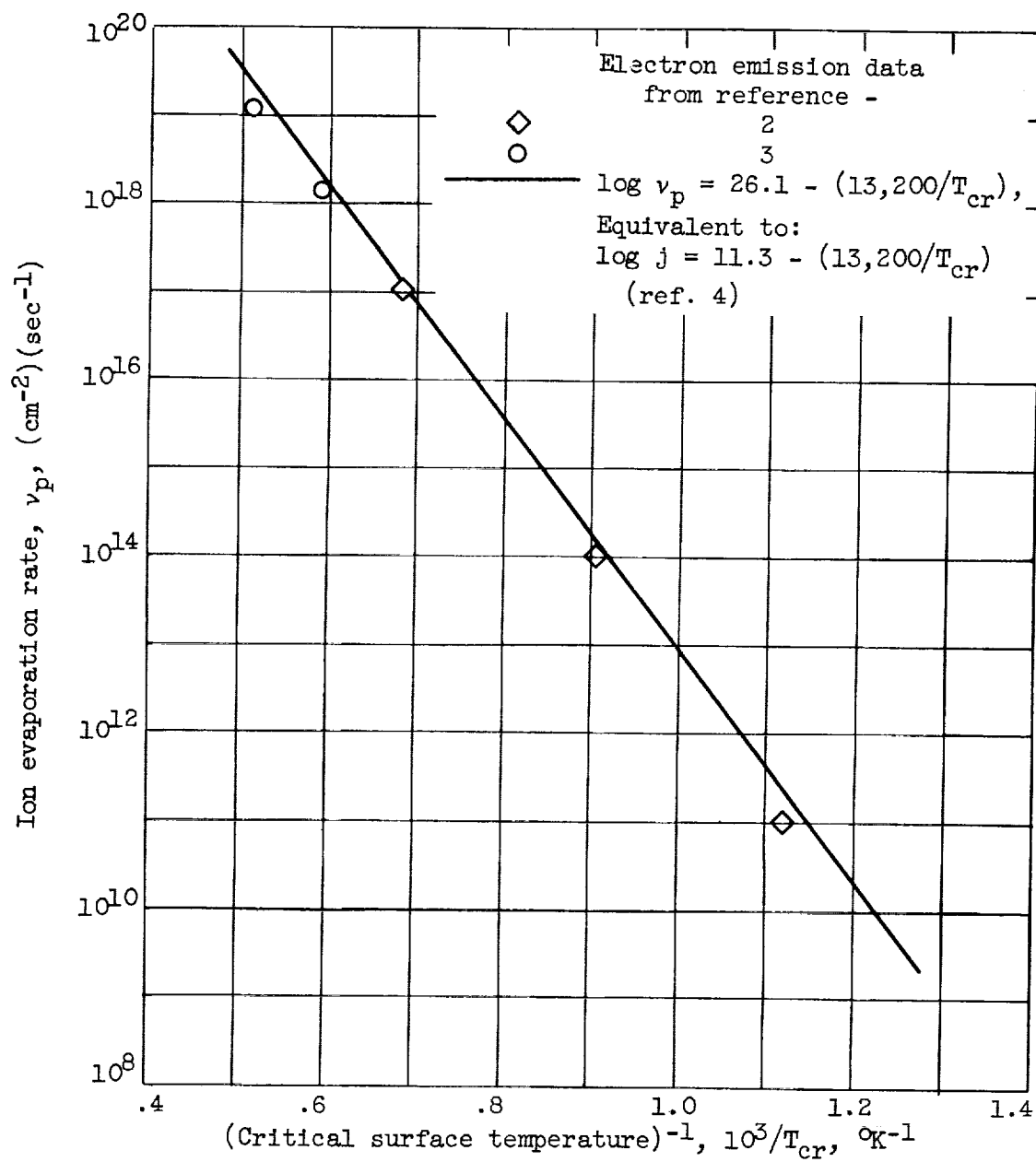


Figure 3. - Comparison of ion current density with critical surface temperatures for system cesium on tungsten.

<p>NASA TN D-1307 National Aeronautics and Space Administration. ESTIMATION OF CRITICAL TEMPERATURE FOR SURFACE ION CURRENTS FROM ELECTRON EMISSION DATA. Thaine W. Reynolds. May 1962. 15p. OTS price, \$0.50. (NASA TECHNICAL NOTE D-1307)</p> <p>Critical surface temperature - cesium ion current density relations are presented for the surfaces rhenium, molybdenum, tantalum, and niobium. A method is described by which these relations were obtained from the electron emission data from these surfaces in the presence of cesium vapor.</p>	<p>I. Reynolds, Thaine W. II. NASA TN D-1307 (Initial NASA distribution: 19, Electronics; 41, Propulsion systems, electric.)</p>	NASA
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